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TOWARDS METROLOGY 4.0 IN DIMENSIONAL MEASUREMENTS

The paper presents the transformations taking place in length and angle metrology related to Metrology 4.0, a measurement strategy resulting from Industry 4.0. Metrology in an industrial conditions is gradually focusing more and more on advanced measurement systems. The coming reality will see the development of communication between systems and their components, as well as the individual sensors belonging to them. The Internet of Things and artificial intelligence as well as the possibility of using augmented or virtual reality will play a momentous role. The demand for these technologies results in the development of new specialized software and hardware solutions, the use and availability of which are diametrically different compared to the past. Also, the use of AI and cybersecurity in metrology is a topic that is receiving increasing attention. Metrology 4.0 is therefore becoming a very important part of the functioning of industry, changing the philosophy and organization of measurements carried out on the basis of new measurement techniques.

1. INTRODUCTION

For many years, length and angle metrology has been experiencing intensive development related to the need for faster measurement processes and increasing accuracy requirements from various industries. The trend of replacing human hands with automated and mechanized equipment, as well as industrial robots, is in many respects resulting in the replacement of simple measuring instruments by measuring systems with a decidedly higher degree of complexity. A graphical representation of this trend is shown in Fig. 1. Such measurement systems function in coordinate measurement technology involving the analysis of coordinate values of measurement points, rather than directly the values of specific features. A coordinate system is defined as an unambiguous representation that assigns to each point in space a finite sequence of real numbers called coordinates. These are converted by measurement software into associated proxies, which form the basis for determining the dimensions and deviations of the measured feature according to its geometric specifications (GPS). Thanks to the global coordinate system, it is possible to unambiguously determine the spatial positions of individual points, and all elements of regular geometry are

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then determined on their basis or by calculation. The following are defined as basic geometric elements: point, line, plane, circle, sphere, cylinder and cone. Merely calculating the basic geometric figures that make up the object to be measured is insufficient in most cases. Information about the interrelationships between them is also needed. Therefore, such parameters as distance, angular position are determined. Deviations, orientation, position and runout are also often calculated. Related filtering techniques require data files and coordinates instead of specific feature values.

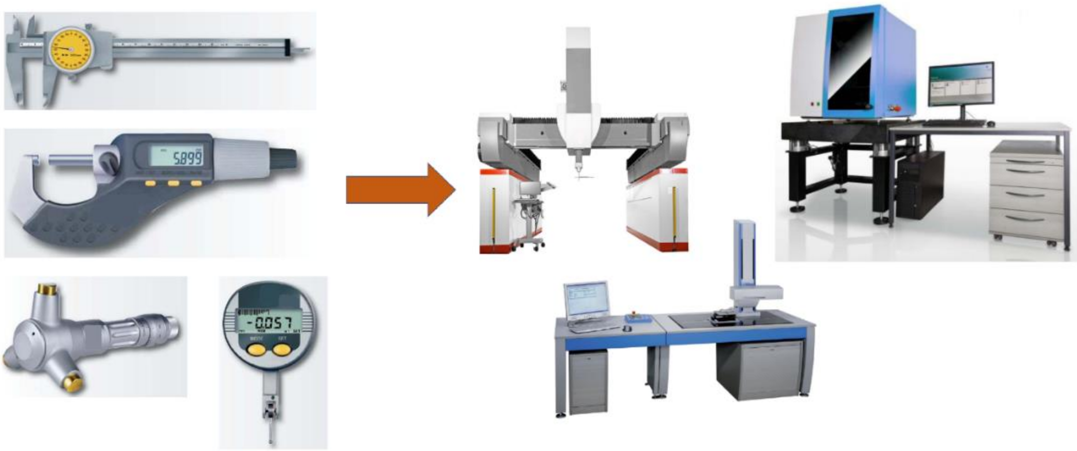

Fig. 1. Trend of replacement of simple measurement tools with measurement systems (courtesy of TESA, Leitz, Otto and Hommel)

The interest in coordinate measurement technology has thus led to rapid industrial growth, producing parts with increasingly complex geometries and increased quality requirements, while keeping manufacturing costs low. A key aspect was that this technology makes it possible to provide a large amount of information about the geometry of components while ensuring the required accuracy and speed of measurement. The ability to automate the measurement process and integrate with CAD/CAM systems, including the measurement of free surfaces [1] and their evaluation against a digital model, also became an added advantage. This has enabled the rapid development of coordinate measurement technology now relying on both contact and optical measurements, which reduce the time to collect a large amount of product information.

Coordinate metrology, thus defined, refers to the measurement of geometric features and therefore refers to the large scale (macro). But coordinate metrology of length and angle also functions at other scales, namely the small (nano and micro) scale concerning surface irregularities and the intermediate (meso) scale, which covers the region when irregularities begin to transform into geometric features, while dimensions (or deviations) become small enough to enter the area traditionally understood as roughness. The boundaries between scales are naturally vague. In order to get a holistic view of the object being measured, analysis across scales is necessary. Metrological verification therefore includes geometric features and shapes as well as surface roughness. Techniques that integrate measurements at different scales are also becoming more common, and individual instruments previously associated with one scale are increasingly boldly entering other scales. Thus, on the one hand, macro techniques are increasingly entering the meso [2] and even micro domain (coordinate measuring machines are beginning to use heads to measure surfaces at the micro scale [3]), while on the other hand, techniques originally considered possible only for measuring surface topography at the micro scale (surface roughness instruments allow measuring shapes) are emerging in this area as their measurement range grows (Fig. 2). These trends are denoted by blue arrows in the figure. All modern measurement systems at these scales function on the basis of coordinate measurement technology, that is, they collect coordinates of points and present selected features based on them.

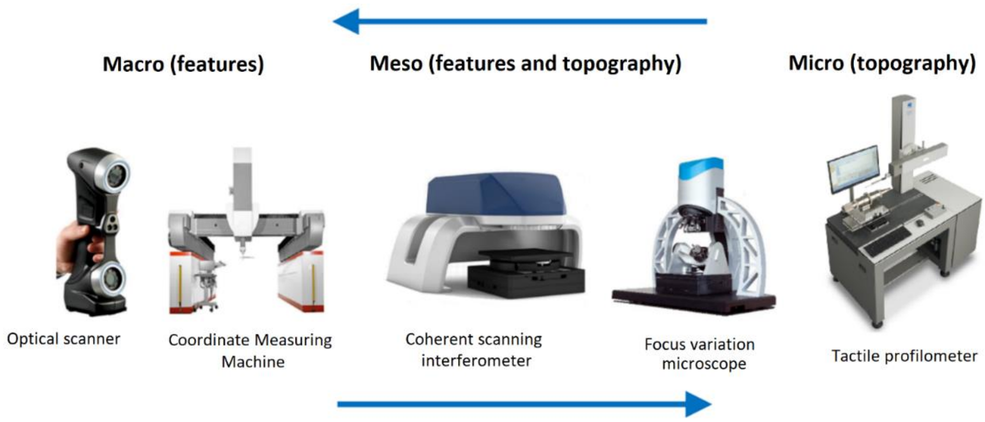

Fig. 2. Scale dependent measurement techniques (courtesy of Creaform, Leitz, Polytec, Alicona and Hommel)

The development of metrology is naturally also influenced by modern manufacturing technologies and design intentions. When designing new assemblies and equipment, designers are reducing tolerances, increasing requirements for functionality. As a result, machine tools in the Industry 4.0 strategy are also producing workpieces to tighter tolerances, which in turn forces measuring devices to operate with smaller maximum permissible errors MPEE. New ways of manufacturing are also emerging, such as additive manufacturing and the associated new applications and requirements for measurement techniques. All these factors are resulting in new measurement devices on the one hand, and new approaches to measurement algorithms on the other. Based on more and more new principles of physics and using better detector resolution and computing unit parameters, instruments with increasing capabilities are being created. Added to this is the increasing automation and robotization and the development of information technology.

2. FOUNDATIONS OF METROLOGY 4.0

Measurement is an integral part of our lives and has accompanied us for centuries evolving with the progress of mankind. Already in ancient times it was realized that correct measurements of various quantities give invaluable knowledge and allow the creation of very advanced designs. From those times come the first length standards and their hierarchy.

During the first industrial revolution, the first vernier caliper was developed and the meter was invented as a unit of length. The second revolution resulted in the start of regular production of the bail micrometer for industry, and the first designs of measuring microscopes and interferometers were developed, as well as gauge blocks. Profile irregularities began to be measured. The metric convention was also signed and the definition of a meter based on the distance of two dashes was adopted.

With the advent of the automotive industry, mass production became more important. The third revolution brought further elements in metrology still known today. The industry developed automated machine tools producing large quantities of parts generating the need for fast and accurate measurement of components in 3D. To realize this, the first coordinate measuring machines were constructed, allowing measurements first in two and then in three axes [4]. The next step was to equip these machines with drives and controls to automate the measurement process and quickly process large amounts of measurement data. The first ideas and designs appeared, allowing the analysis of irregularities in three dimensions, i.e. measurements of surface topography.

Industry 4.0, on which a great many different studies have already been written, brings with it a completely different outlook especially in terms of IT. Cyber-physical systems, the Internet of Things, networks and cloud-based big data, artificial intelligence and robotics are all very important elements that have also found their way into Metrology 4.0 sometimes also called Metrology of the Future. Industry 4.0 itself appears to be a strategy using various technologies to create autonomous and intelligent manufacturing systems with the ability to self-configure and self-monitor, and even repair themselves. For this, it is necessary to develop sensors, capable of detecting a wide variety of factors, to acquire information about the state of processes and their components [5]. This, in turn, will enable multi-criteria optimization of processes and more efficient use of resources [6, 7]. Machines and technological equipment will have to function in readiness for rapid reconfiguration (reconfiguration). This is also the only effective answer to the problems of modern industry: lack of hands to work, shortage of skilled labor and growing ecological requirements. The fourth revolution changes not only what we do and how we do it, but also who we are, it changes engineering approaches, business, economic and social dependencies, thus affecting not only machines and systems, but all aspects of human functioning in the 21st century. To cope with this, a metrology engineer will need to have multidisciplinary knowledge that includes - in addition to metrology - mechatronics, automation and computer science. For this reason, it is already less of a problem for many growing companies to invest in equipment compared to investing in a human to take care of it. Measuring devices and the new technologies in them require knowledge and understanding of what is happening during the measurement process in order for the measurement result to be a reliable reflection of reality.

3. MEASUREMENT TECHNOLOGIES FOR METROLOGY 4.0

The Metrology 4.0 strategy is not only an approach to measurement, but also measurement systems based on various principles derived from physics. It can even be said that these systems derived from coordinate measurement technology have created the possibility for at least some of the elements of Metrology 4.0 to exist, allowing, for example, the creation and work on large data sets (big data). One such technique is optical scanning. Its history is about 20 years, but despite such a short period of time, it can be seen to have developed significantly and gained considerable popularity in the market. Current scanner designs are therefore very advanced. Laser scanning technology [8] is steadily displacing the structured light used in the previous generation, giving - in addition to very good accuracy parameters - mainly solutions that do not require tripods and negligible sensitivity to changes in reflectivity and external lighting [9]. More recently, blue light has been used. A schematic image of exemplary laser scanners is presented in Fig. 3.

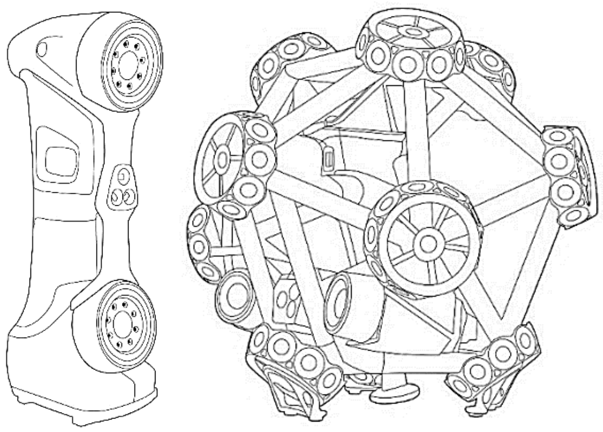

Fig. 3. Schematic image of sample laser scanners

Referring to the spirit of Metrology 4.0, the scanners also work in a robotic version, as shown in Fig. 4. The concept presented here is based on a scanner mounted on a robotic arm and a tracker that tracks its position. The object is mounted on a rotary table that provides an additional axis in the measurement system. In addition, the solution has a set of cameras and software that allows a remote user to participate in the measurement process remotely. The idea has proven to be a particularly successful solution for the pandemic period.

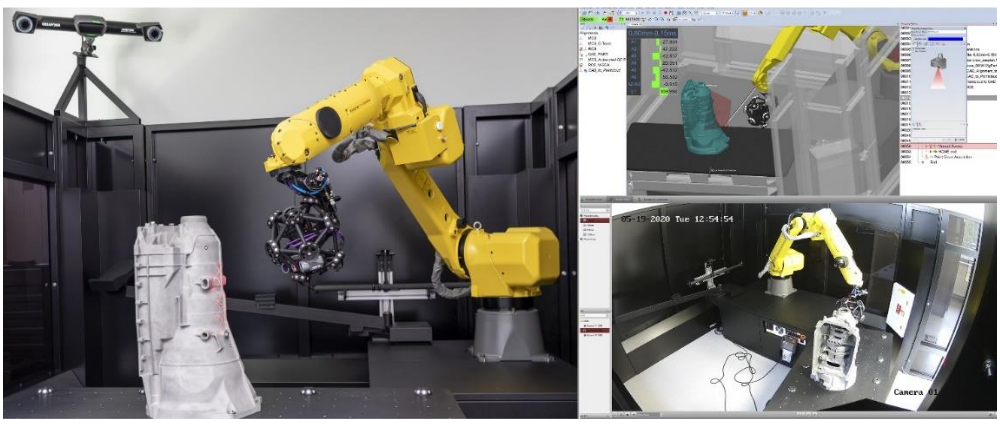

Fig. 4. Robotic scanning workstation (courtesy of ITA)

In addition to scanning with a collection of laser lines, laser line sensors are becoming more common. Their operation is particularly justified in situations where it is necessary to provide rapid inspection of a limited number of geometric features. This is often the case in the production line, where such systems enable in-line verification, i.e. where the detection of possible defects is most desirable [10]. An example configuration of a station based on laser line sensors is presented in Fig. 5.

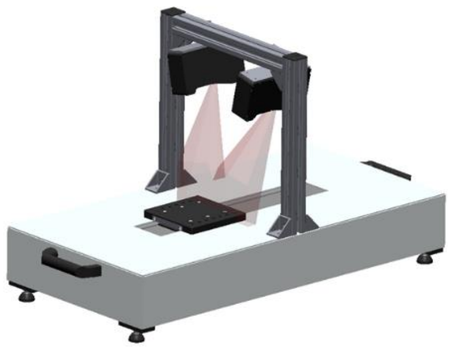

Fig. 5. Configuration of a station based on laser line sensors

The youngest part of coordinate metrology in terms of physics is technical computed tomography. The devices operating in this technology are based on *X*-rays [11]. Thanks to their use, it is possible not only to image defects in objects, but also to measure geometric features, even completely invisible ones [12, 13]. The design of a tomograph for technical applications consists of a lamp, a manipulator with an object holder and an image detector mounted on a common frame. A very important component is the software, through which artifacts are removed on the one hand, and geometric features are calculated on the other. In addition, it is required to provide sufficiently stable thermal conditions inside for correct verification of metrological parameters [14]. Technical tomographs, due to their parameters, are intended for a wide variety of applications on a macro scale [15], but there are increasing ideas to apply them to the measurement of surface irregularities [16, 17], primarily due to the possibility of faithfully reproducing re-entrant surfaces [18], which is unattainable for both contact and optical techniques. A schematic image of such a tomograph together with a robot feeding and receiving measured objects is shown in Fig. 6.

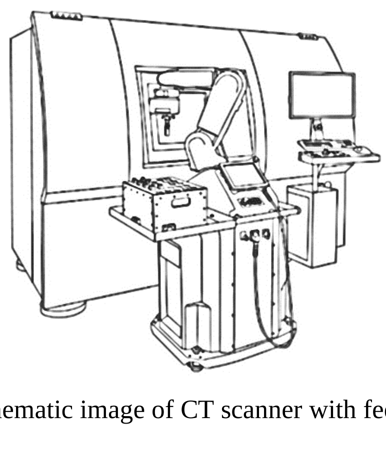

Fig. 6. Schematic image of CT scanner with feeding robot

As can be seen from the above analysis, cobots and robots are becoming an everyday occurrence in Metrology 4.0. Their use makes it possible to become increasingly independent of humans, as the most unpredictable element of the measurement process. The operator is also, from the point of view of thermal phenomena, a very important element, negatively affecting measurement uncertainty. This also makes the future of measurement systems associated with increasing automation. The use of drones is also being seriously considered (Fig. 7).

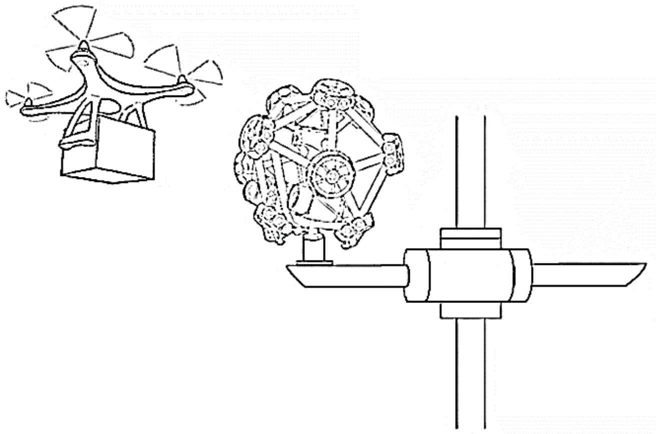

Fig. 7. Drone moving the measured object around the scanner [19]

Multisensor solutions are also an important part of Metrology 4.0 [20]. The simplest version of such a solution is the use of a contact head (with different tips) and microscope optics, resulting in an optical-contact CMM. In such designs, the two heads have a correlated mutual position, allowing part of the workpiece to be measured by contact and part by optics. Multisensor devices are developing toward smaller scales. Increasingly, tips for contact measurement of surface irregularities and even optical heads for micro-scale measurements, such as interferometric, are being mounted on the CMM. The question of how much work the machine itself does and whether multisensor measurements (especially at different scales) are effective, but whether it's worthwhile to implement them with two separate devices, remains an ever-present one. This, of course, depends on the specific measurement task and the measurement site - the laboratory will always look more for universal solutions and production for specialized ones.

At the micro and meso scale, it is also worth mentioning optical surface analysis techniques, which are slowly becoming present not only in the scientific world, but also in the industrial world. At this scale, it is necessary to be aware of wave-like phenomena, making the replacement of contact profilometry, which was very much hoped for, a complex process [21]. Optical measurements make it possible to obtain data from the surface in many times less time and without contact with the measured object, which translates into great interest from users. Nevertheless, the representation of surfaces by optical and contact techniques is not the same [22], which led to the terms mechanical surface (obtained by contact measurement) and electromagnetic surface (obtained by optical measurement).

The quest to find a fast and universal method for measuring surface topography at the micro-scale has led to the development of a wide variety of measurement techniques [23].

They can be divided [24] into scanning (which evaluates surface irregularities based on a set of individual scans) and surface-based (which evaluates irregularities based on averaging and adopting a model to describe the measured irregularities). The latter have been adopted for some time now only in single applications [25, 26, 27], hence more attention should be paid to scanning methods. We divide them into profile scanning methods, which evaluate topography based on a set of profiles and can be implemented as 2D (profile) and 3D (surface), and image scanning methods, where evaluation is based on a sequence of images. Among profiling scanning methods, the most popular include contact profilometry [28], auto-focus point profilometry [29], confocal profilometric heads [30], scanning tunnelling microscopy [31] and atomic force microscopy [32]. Scanning imaging methods (using vertical scanning or image merging) include phase shift interference microscopy [33], scanning coherence interferometry [34], confocal microscopy [35], focus variation microscopy [36], digital holographic microscopy [37], scanning electron microscopy [38] and transmission electron microscopy [39]. Metrology 4.0 in contact profilometry is an extension of CNC measurement options. The bench can feature automatically realized displacements in linear and rotary axes. Once all the measurement locations are programmed, the measurement is carried out without operator involvement. This applies to unevenness and contour measurement. The main disadvantage of contact measurements, especially in 3D terms, is the execution time due to the need to slowly move the contact tip over the surface to be measured, which in turn causes additional sensitivity to thermal changes [40, 41].

The most promising of the optical techniques seem to be focus variation microscopy (FVM) and coherent scanning interferometry (CSI). In modern devices working on the basis of CSI, we use white light or at least polychromatic (a portion of the visible band) interferometers instead of a single length of light. The incident light beam in correlation with a reference beam allows us to obtain a clear image of the striations at a certain height, and a three-dimensional effect is obtained by scanning the entire measurement range in the vertical axis. The size of the measured area in one shot depends on the magnification and resolution you want to achieve. There are systems that allow measurements as small as fractions of a nanometer, the ranges of some allow us to measure shape errors and dimensions, firmly entering the meso scale.

Perhaps the most widely used optical instrument for measuring surfaces at the micro and meso scale in industrial applications is the focus variation microscope. And although only a dozen years have passed since the first constructions of this type, the technology has advanced so much that systems from the 1920s give a significantly better image than the oldest ones. In this system, the essential element is a microscope that shows a sharp image at a certain height extended by a precise vertical axis that allows collecting such sharp images throughout the measurement range. All the collected shots with good measurement data are then transformed into a spatial three-dimensional image. Such a microscope also covers the micro and meso scales, so in addition to topography [42] of the surface it is also excellent for measuring geometric features in a wide variety of applications [43]. In this regard, there have also been very significant developments in recent years. In addition to the standard applications of surface topography measurements derived from tribology and related to plateau honed surfaces [44] or plasticity index [45], biotribological applications [46], primarily related to activities carried out on the human body, are increasingly appearing.

In addition, a whole metrology related to additive manufacturing [47] has emerged, conceived somewhat differently from its classical counterpart. Structures made with these techniques tend to create surfaces of a completely different nature, and hence, for example, the ideas described above using microscale tomographs. Besides, it is worth remembering that the filtering of the signal obtained from the surface, which is common at this scale, is related either to the way the surface is processed or to the functional highlighting of certain characteristic features of the surface. From this point of view, the classical division into roughness and waviness for incremental techniques is not justified, which further necessitates the search for other analytical methods.

4. INFORMATION TECHNOLOGIES IN METROLOGY 4.0

The young generation, entering the market, perceives the world as digital, preferably in 3D, in real time and with an immersion effect, in what is going on, whether it is social media or professional work. In Metrology 4.0, challenges also arise in the IT area. Starting with big data, or datasets containing large amounts of information, the first element of this in length and angle metrology was the measurement of surface topography at the micro scale [48]. The development of single-profile measurements into a set of profiles and later also images resulted in data sets that were difficult to process by the computer systems of the time. Only progress here resulted in pushing measurements towards an increase in the number of profiles and representation of surfaces (here a large role is still played by graphics cards today). Another issue was the scanning processes described above, where the ability to collect millions of points in a very short time created huge data sets. Here, appropriate software allows you to extract those points that are necessary to represent the nature of the surface through a grid of triangles with different sizes of basic elements [49, 50].

A further use of big data is computed tomography. Here, the pixel turned into a voxel, which entailed a further increase in the size of data files. Techniques for extracting surfaces from spatial data have emerged, which is essential for length and angle metrology. As with scanning, there is a need here not only to store these datasets, but also to match them to CAD datasets, which further necessitates the development of hardware on the one hand and thoughtful software procedures on the other.

In the coming reality, communication, which plays a very important role between people, will also develop between systems and their components, as well as the individual sensors belonging to them. According to the IoT concept, all components and even objects are uniquely identifiable. Thus, collections of various sensors will be installed in measuring devices, monitoring their parameters and transmitting the collected information to further analysis and decision-making systems. Among this information will naturally be those related to the measurement process being carried out (the object being measured, the selected head and stylus, the measurement conditions, etc.) and the environmental conditions (temperature, pressure, humidity), but also those related to the condition of individual components of the device. Based on these, it will be possible to decide whether to stop the measurement due to the possibility of an increase in measurement errors.

Augmented or virtual reality is also an element of communication. It mainly benefits areas where the integration of these technologies is problematic or financially demanding [51]. Augmented reality relies, among other things, on the ability to obtain more information using simple communication tools, such as a smartphone. On its screen, the view of the machine can show information about the temperature at selected locations, the operator, the measurement time, the task, etc. An example image is shown in Fig. 8.

Fig. 8. Sample image from an augmented reality application

Virtual reality is a further extension of measurement capabilities, especially in terms of simulating the measurement flow. The ability to realize a measurement on a virtual object means not only earlier detection of errors in the measurement program on a single device, but also simulation of measurements at multiple scales using different measurement systems.

The use of artificial intelligence or AI in metrology is a topic that is receiving increasing attention [52]. It is predicted that it will simply become a necessity in the near future, as the cost of hiring an employee and fully preparing him or her for modern measurement workstations is a time-consuming process. Without this, on the other hand, a formal or interpretive error with significant consequences may be made due to lack of skills. Besides, although the increasing number of options in measurement software increases its capabilities, from a psychological point of view, too many options to choose from is a source of stress, a sense of paralysis and dissatisfaction for humans [53]. A hint of this choice, or at least the existence of default options for a given application, will make work much easier.

Based on a growing number of publications, the importance of AI's impact in I&M (Instrumentation and Measurement) is very high [54]. For measurement instruments, AI can be used to select measurement conditions and strategies and filtering techniques, among other things. In addition, each measurement technique still has specific elements that can also be supported for the benefit of the operator. This support is especially important for the less skilled and for new items to be measured, when existing experience cannot be used directly. Macro-scale artificial intelligence can automatically load a CAD file for the object to be measured, select - depending on the instrument - the probe head and pins, scanning density and illumination parameters, X-ray-related parameters, etc., and propose a measurement procedure (strategy) according to the feature, including a suitable data filtering method. Once the measurement procedure is completed, calculations of features and measurement uncertainty are made based on data from the environment. For the micro scale, for example, this will be the loading of surface data on how it is made, functionality, material, etc., based on which AI will suggest (or exclude) a specific measurement technique. It will also suggest measurement conditions, related to tips or lenses and lighting, depending on the measurement technique, as well as the measurement field and nesting index depending on the expected parameter values, along with the stitching procedure. For the obtained data, the system will select a filtering method, which, with the number of options currently available including Gaussian (linear and robust) [55], morphological [56], spline [57] wavelet [58] or multiscale [59], is, from the user's point of view, a very difficult task, but an important one in order to show surface features and calculate parameters correctly [60]. Such a system based on artificial intelligence will be a great support for the user, allowing efficient and fast decision-making, using data and premises from the knowledge base created and developed on the basis of daily tasks.

The last of the issues worth mentioning when discussing IT in metrology is cybersecurity. Security of measurement data and more is an important issue in the context of the operation of companies using Industry 4.0 strategies. Unwanted interference with design and technology data leads, of course, to erroneous assumptions and performance parameters. An attack on measurement data can lead to the belief that feature values are out of tolerance, when in fact nothing of the sort has happened. It can also lead to the opposite situation – conveying the information that the item is correct, when the actual results obtained turned out to be beyond the tolerance limits. To avoid this, increasingly sophisticated IT security measures are being used. Companies are also beginning to look more readily at building internal networks for such purposes, with no access from outside the corporation, using only wired links. This problem will intensify with the development of computer technology, especially when quantum computing becomes more common.

5. CONCLUSION

In summary, Metrology 4.0 is becoming a very important part of industry operations, changing the philosophy and organization of measurements carried out based on new measurement techniques. It often entails more demanding conditions, as optical measurements, for example, require near-perfect surface cleanliness, in addition to being sensitive to the way and configuration of surface illumination with external light. They also often require better isolation from the environment from the point of view of vibrations. It is also worth bearing in mind that coordinate measuring machines with contact heads - although slower and collecting fewer measurement points in a given time – still allow much smaller measurement uncertainties than optical scanning or computed tomography.

Metrology is also changing in terms of the services offered by specialized measurement laboratories. The concept of a robotic scanning system with the option of remote participation in measurements, presented when describing scanners, is a good example of this. This is because it raises the idea of outsourcing and the question of whether surely a particular measurement system is necessary in a given company, or whether it is better to outsource measurements? Among its advantages - in addition to the fact that you don't have to invest in a measuring device - is that you don't need to hire specialists, and you can use highly qualified personnel at the contractor. Verification of the supplier should naturally be carried out very meticulously, and a good indicator when choosing a partner is that it is accredited in accordance with ISO 17025. Using the services of such an accredited laboratory provides full assurance that the results are reliable and unbiased, and that the accredited entity has personnel with adequate knowledge and competence, appropriate equipment and uses reliable and correct testing methods. It is also not insignificant that it is also the responsibility of the one performing the measurements to calibrate the measuring instruments.

The world is slowly starting to talk about Industry 5.0, so what can we expect from Metrology 5.0? This, of course, is not yet fully defined. Nevertheless, it is expected that the industry – in addition to innovation efficiency and productivity – will drive environmental and social change, putting the well-being of the worker at the center of the production process. This is in response to the changing skills and training needs of the workforce, ultimately increasing competitiveness, with the goal of ensuring the well-being of life beyond the workplace as well, while using the planet's natural resources more efficiently. It should also contribute to better resilience to the global shocks that have affected societies in recent years. This change in metrology will be initiated by even more widespread use of information technology, including, of course, artificial intelligence and related learning systems. Systems will be based on objects working together, with the definition of connections using the idea of blockchain. But proper data management will also be important, as data will grow rapidly in the coming years, thanks to 5G technology and sensor developments. Thus, event-managed applications will appear, allowing to select those that are most relevant, so that the measurement result reflects reality and its interpretation is not overly complicated for the user. Their functioning will reflect the mechanism: event - information - adoption of information. There will be a huge scope here for startups, which will find it easier to adapt to the changes than large organizations. Meeting these challenges will therefore be very important for the industry, so that the industrial plant will be prepared for young engineers at least as well as they will be prepared for their work.

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